Solar Water Heating Systems: A Review on Contemporary Design and Emergent Technology using PCM for Increased Performance

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ABSTRACT

This study highlighted the specificity of solar water heating systems, investigating their financial benefits and discussing their economic advantages. Several studies have shown that solar water heaters' effective performance and the best cost savings were obtained during the hot seasons. New developments in solar water heaters have been discussed in detail. According to numerous researches, the highest quality performance of solar water heaters and the best cost savings were achieved when the system was integrated with innovative components such as Phase Change Materials (PCMs), heat pipes, and turbulators. Emergent technologies using PCMs have shown excellent results, increasing solar thermal efficiency. This technology presents great potential not only for domestic applications but also on an industrial scale.

Keywords-solar water system; emergent technology; collector; PCM; performance

I. INTRODUCTION

The building sector around the world is projected to consume up to 100 quadrillion BTU of energy in 2035 [1]. In many countries, population growth and rapid economic development have led to a rise in energy consumption that accelerates the depletion of local resources and increases greenhouse gas emissions [2]. Renewable energy sources are exploited to generate electricity. Solar thermal energy is a technology to harness solar energy and convert it into thermal and/or electrical energy. In 2016, the installed thermal heat capacity globally reached 456 GWh [3]. Although the contribution of thermal solar heating is underestimated in many countries, this contribution is the second largest energy production after wind energy and is more important than the photovoltaic solar energy production. Solar thermal energy production competes with conventional renewable energies such as hydroelectricity and biomass [4]. Heating water with fossil fuels requires significant energy consumption and poses economic and environmental problems. Solar Water Heater Systems (SWHSs) are a modern alternative energy source to provide hot water, replacing and limiting fossil fuels consumption. SWHSs need increased public awareness of their benefits to enlarge their adoption and are classified among the environmentally friendly contributions of renewable energy [5].

Solar water heaters can be categorized into two main types: active and passive. Both systems harness the energy of the sun to heat water but differ in their operational mechanisms, efficiencies, and applications [6-7]. They are essentially based on solar radiation or the heat of heat transfer fluids from a collector to heat water [8]. Solar water heaters can eliminate 50 tons of carbon dioxide emissions in 20 years [9]. A conventional SWHS consists of a panel with solar collectors and an insulated tank with a size large enough to store hot water and maintain the desired heat. There are different types of solar water heaters, such as integrated storage solar water heaters, flat plate thermosiphonic units, and evacuated tube thermosiphonic units. The integrated storage SWHS is made up of solar collectors and water storage tanks in one unit [10]. These systems are simple in terms of manufacture and less expensive than other systems while being able to produce hot water up to 200 l/day [11-12]. The disadvantage of integrated solar water heaters is the increase in thermal losses during the night due to the water tank [13-14]. These heat losses are still poorly understood despite several encouraging results [15-16]. Indeed, several studies have investigated the improvement of the thermal performance of SWHSs to reduce these losses [17-19]. In addition, many studies have investigated technologies to develop energy-efficient and high-performance solar power systems [20]. These systems can be used in different types of engineering applications depending on the production mode, such as cooling and heating systems in buildings [21-22], SWHSs [9, 23], solar air heating [24-25], solar storage tanks [26], photovoltaic thermal systems [27-28], solar thermal power plants [29-30], refrigeration and air conditioning [31-32], solar stills [33-34], textile industry [35], and smart electronic devices [36-37].

This study illustrates the world trend to use renewable energy, particularly solar energy, encouraging the development of technological solutions for water heating. It also highlights the performance of SWHSs, analyzes their financial benefits, and compares their economic advantages with other water heating systems. In addition, the efficiency of different collector materials is investigated, along with a comprehensive review and description of the performance of various solar collector designs as well as the challenges associated with the installation of SWHS.

II. RENEWABLE ENERGY POLICIES AND INITIATIVES AROUND THE WORLD.

Worldwide, many governments have introduced and implemented energy management systems and policies related to energy efficiency and renewable energy schemes. Table I shows the main initiatives. Based on these strategies, the development of SWHS was encouraged through different research programs and grants.

TABLE I. RENEWABLE ENERGY POLICIES AND INITIATIVES AROUND THE WORLD [38]

Country	**Renewable energy policies and initiatives**
Australia	The government decided to create and maintain a regulated and competitive energy market for the propagation of energy harnessing using cost-effective, efficient, and clean technologies
Brazil	Focus on biofuel-based projects owing to the presence of the Amazon Rain Forest on its mainland
China	Takes the issue of climate change seriously and has put in place several policies regarding the conservation of ecology and environment for sustainable development and better socio-economic future of the country
EU	20% reduction in the emission of greenhouse gases, 20% increase in overall energy efficiency, increased contribution of renewable energy by 20%, increased contribution of biofuels for transport by 10%.
USA	Does not have an effective policy regarding renewable energy systems

III. CONTEMPORARY PERFORMANCES

SWHSs have many advantages, such as financial benefits, energy performance, and efficiency.

A. Financial Benefits

To study the feasibility of SWHSs, an economic evaluation is essential to improve consumer awareness of their benefits. In [39], the cost of SWHS and its financial benefits were studied in a residential area in Pakistan. The replacement of water heating using electricity by SWHS made it possible to save €430.95, while the replacement of water heating using natural gas with SWHS saved €67.81 in energy costs per household per year. The cost of installing solar water heaters is high but can be recovered after a period of use. The payback period for SWHS installation varies from 1.16 to 1.38 years for electricity; however, the payback period for natural gas water heaters is longer and varies between 6.95 and 8.27 years. According to [40], replacing electric water heating with SWHS saves 4163.98 kWh of electrical energy per year. An SWHS reduces CO_2 emissions by 2206.9 kg, SO_2 by 2.08 kg, and NO_3 by 75 kg per year. Materials and installation costs for solar water heaters have been estimated at $337,000. Replacement of electric water heaters saves 1146 GJ. With the cost of one kWh corresponding to $0.12, the annual savings on electricity costs would be $37,606.30, and the repayment period would be 9.2 years. Due to the local economic recession and deflation over the past few years, net worth has not been taken into account. Thus, the discount factor cannot be determined as a result of economic growth. Furthermore, the estimated cost of electric water heaters is $85,665.87. Based on these financial studies, the first net cost of a SWHS would be 249,858.80 USD. With savings in electricity, the repayment period for installation and material costs would be only 6.9 years and can be further shortened. The thermal transmission of solar water heaters varies depending on the architectural design and the orientation of the collectors. Right positioning and orientation make it possible to have a considerable part of the solar radiation, which would be converted by the SWHS to heat water. In [41], it was shown that using PV/T collectors with west orientation can reduce heat gain by more than 50% in summer. For domestic applications, electricity consumption depends on the mode and frequency of electrical appliances use. The main obstacle to an SWHS installation is the high cost of installation and heating system equipment. To encourage the installation of SWHS, governments need to introduce economic incentives and benefits to users. As a result, installation and hardware costs will be more affordable and attractive to consumers. Table II presents the monthly electricity consumption of centralized SWHSs and conventional unitary electric radiators. These measurements show that the electricity consumption of electric heaters is higher than that of SWHSs. Furthermore, consumption is very high in December, January, February, and March.

TABLE II. MONTHLY ELECTRICITY CONSUMPTION OF CENTRALIZED SWHS AND CONVENTIONAL UNITARY ELECTRIC HEATERS IN HONG KONG [42]

Month	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Electricity consumption of unitary electric heaters (GJ)	207	175	185	174	170	160	162	162	162	180	185	205
Electricity consumption of centralized solar water-heating (GJ)	125	80	95	110	93	75	65	65	70	75	70	103

According to [42-44], the lack of information on the lifespan of solar water heaters and the low cost of electric resistance water heaters do not encourage consumers in Brazil to use SWHS. In [45], it was reported that it is more economically profitable for public services to finance large-scale SWHS projects for low-income populations. The results show that given the high costs, the low-income population does not have the means to install and buy SWHSs. In addition, SWHSs have several advantages for consumers, such as financial savings in electricity costs and energy savings. Solar water heating is more feasible if the payback period for installation and material costs is shorter [46]. The diffusion of SWHS in different areas is due to national and regional subsidy programs, tied to government programs. Furthermore, the size of SWHSs is related to the volume of hot water used daily by consumers. The surface of the solar radiation collectors and the hot water storage are calculated according to the hot water consumption of each consumer and the climate of each period and place.

B. Energy Performance

In [5, 35], high-rise centralized SWHSs were evaluated, and in [40], thermal solar collector networks were installed at great heights to support hot water consumption. According to meteorological data, the annual average efficiency of solar collectors could reach 38.4%. Thus, the solar fraction reaches 53.4% with an installation cost recovery period of 9.2 years. With the increase in electrical energy consumption expenses, the return on investment would be even shorter than the classic payback period. Table III illustrates the monthly thermal gain of the solar collector arrays on the south and west façades. The simulation results of the thermal model show that from the southern network, thermal gain can be obtained during the cold season (September - March). On the other hand, from the western network, the thermal gain is higher during the hot season (April - August). This variation trend agrees with the incident solar radiation on the façades of the solar collectors. In addition, the use of two solar panels gives an important performance throughout the year (except January and April) and a relatively stable thermal energy production. Furthermore, the annual thermal gains of SWHSs are different depending on the location of installation. The thermal gains are higher in the south than in the west, corresponding to 478 GJ in the south and 426 GJ in the west. Therefore, a total solar radiation collector surface of 840 m² can produce 904 GJ per year. Consequently, overall performance is 1.08 GJ/m^2 per year. On the other hand, based on solar radiation measurements, the incident solar radiation on the south facade is 1216 GJ, and on the west façade it is 1141 GJ.

TABLE III. MONTHLY THERMAL GAIN OF ARRAYS OF SOLAR COLLECTORS TAKEN INTO ACCOUNT SOUTH AND WEST FAÇADES OF BUILDINGS [48]

Month	1	2	3	4	5	6	7	8	9	10	11	12
Thermal gain in south (GJ)	40	48	41	22	25	26	27	34	42	57	65	55
Thermal gain in west (GJ)	19	29	34	29	41	54	59	50	40	32	23	19
Total	59	77	75	51	66	80	86	84	82	89	88	74

C. Efficiency

Table IV presents the average efficiency of collectors according to their base materials [49]. The results show that copper and aluminum solar collectors have the lowest efficiency of 56 and 59%, respectively. Black- and blue-coated copper solar collectors have higher efficiency than aluminum collectors, with 63 and 60%, respectively. On the other hand, vacuum-tube solar collectors have the highest yield with an efficiency of 75%. Solar collector usage is linked to the payback period.

TABLE IV. AVERAGE EFFICIENCIES FOR DIFFERENT COLLECTOR MATERIALS [47]

	Black coating selective Cu	Blue coating selective Cu	Cu solar collector	Aluminum solar collectors	Vacuum tube collector
Efficiency %	63	60	56	59	75

Despite the low competence of copper or aluminum solar collectors, these types of SWHS are the most widely used in the world, mainly due to their lower cost, which is a key factor in convincing the user to install an SWHS [5]. The SWHS application size plays an important role without involving the selection of the right solar collectors. Large-scale applications, such as industries, large housing estates, and public swimming pools, require a big number of plates and solar collectors to cover the need for hot water. These applications require large areas and cost too much to install [9]. Despite their high installation and material cost, high-efficiency solar collectors for heavy use are the best choice, as they provide high energy savings and shorter payback periods. Unlike large-scale applications, residential applications require a low unit cost with high hot water efficiency. Therefore, the cost of collector installation and maintenance, the equipment cost, and their efficiency are important factors in the choice of SWHSs. Based on these reports, the cost and efficiency of SWHSs with aluminum collectors and vacuum tubes are the best choices for the production of thermal energy and heating water.

D. Different Material Specifications

The base material of the solar collectors has a strong influence on the efficiency and appeal of SWHSs. The systems used are copper, aluminum, copper with selective blue or black coating, and vacuum tube collectors. Table V shows the material specifications for the manifolds. Each material has its specifications [47]. As the black selectively coated copper collector has the highest length and width of 187.5×88 mm, this header material has the highest gross surface area. In addition, each collector has a different absorber material. For a copper with black selective coating collector, the absorber material is a selective copper coating. For a blue selective coated copper collector, the absorber material is a selectively coated copper tube. For copper or aluminum headers, the absorber materials are special black-painted copper and black-painted aluminum pipes, respectively. In addition, the collector's front cover varies depending on the SWHS and the collector material. The front cover of copper collectors with black selective coating is made of tempered solar glass. On the other hand, the other collectors (aluminum, copper, and copper with blue coating) are tempered regularly. From a cost point of view, the most expensive material is the copper manifold with black selective coating and the vacuum tube manifolds which are equal to \$704.63, and the least expensive is the aluminum one which is equal to \$422.78.

TABLE V. MATERIAL SPECIFICATIONS FOR THE MANIFOLDS IN THE COLLECTORS AND EFFICIENCY OF SWHS [49]

	Black coating selective copper thermosiphon	**Blue coating selective copper collectors**	**Copper solar collector**	**Aluminum solar collectors**	**Vacuum tube collector**
Dimensions (mm)	187.5×88	185.5×86	186×86	187.5×87.5	-
Gross area (m^2)	1.65	1.6	1.6	1.65	1.6168 (for 20 tubes)
Absorber	Selective coating copper	Copper tubes with selective coating	Special copper collectors painted black	Black-painted aluminum pipes	$Cu/AL/SS/N_2$
Front cover	Tempered solar glass	Regular tempered	Regular tempered	Regular tempered	-
Price ($)	704.63	598.94	528.47	422.78	704.63

E. Technical Specifications

Although SWHSs with lower standard efficiency solar panels are widely used, there is still significant power-saving potential in the utilization of more efficient panels [7, 48]. The use of more efficient solar collectors shows potential savings of 65-71% for split systems and 83-91% for thermosiphon systems. The performance of SWHSs may vary in the solar panel orientation as opposed to the north; for example, the east and west orientation of the collector can result in up to 80% reduction in electricity saving. South- and center-oriented collectors result in not only a significant drop in energy efficiency but also a critical level of protection from Legionella. Performance is also greatly affected by the tilt angle of the solar panel. For example, mounting collectors vertically on a building façade reduces the solar fraction and Legionella, depending on latitude. Standard dust accumulation levels in solar panel glass are reduced by 5% compared to clean solar panels, resulting in a 20-24% increase in SWHS power consumption. Under extreme dust accumulation, for example, a 64% reduction in transmission, the annual power consumption of the SWHS increases by a factor of 5-6.

IV. TYPES OF SOLAR COLLECTORS

A very important aspect in improving the energy efficiency of a SWHS lies in the formulation of collector design features: the type and size of the CPC reflector, combined with materials with improved optical properties, and the low iron glass or double glass application for the transparent cover of the absorbing surface [20]. In [49], a storage solar collector with storage tanks was presented, where the accumulator was made of six copper tubes with an outer diameter of 80 mm, the pipes were painted with regular black matte paint, the copper pipes were connected in series with an outer diameter of 15 mm, and a thin layer of paraffin was placed under the absorber to keep the heat from the sun. During sunny hours, liquid paraffin acts as a heat source and transfers heat to the absorber. Rigid styrofoam panels were used to insulate the system. The results demonstrated that the system could keep the collector plate temperature above 40°C for more than 4 hours after the sun's rays dropped in the afternoon.

Some studies used Phase Change Materials (PCMs) in solar collectors, which can be categorized into three main types: organic, inorganic, and eutectic. Each of these types has its own set of advantages, limitations, and potential applications [50]. In [51], a PCM-integrated flat plate collector was designed and manufactured. Nine risers were attached to the top surface of the absorber plate while 37 fins were attached to its bottom surface. PCM was added to the underside of the absorber plate. The riser-absorber fin configuration acts as a heat exchange unit, swaping thermal energy between the PCM and the water, while the fins increase the heat transfer area between the PCM and the absorber plate. In this study, two PCM types were used: (i) paraffin and (ii) paraffin nanocomposites containing 1.0 wt% of 20 nm nanocopper particles. Three case studies, without PCM, with PCM, and with Cu-PCM nanocomposites, were conducted at 10°, 20° and 30° tilt angles. At the end of the 24-hour run, the system without PCM had a tank temperature of 35.1°C at 7:00 am. On the other hand, the tank temperatures of the PCM and Cu-PCM nanocomposite systems were 40.1 and 40.7°C, respectively. For each material, the efficiency of SWHS was variable with a best angle of inclination equal to 10°. The efficiency was around 52.0% for the system with the Cu-PCM nanocomposite, 51.1% for the system with PCM, and 47.6% for the system without PCM. The thermal conductivity of the nanocomposite is 24% higher than that of pure paraffin wax. With the addition of paraffin wax collectors, collector competence increased by 6.9%. On the other hand, the addition of CuPCM nanocomposite improved efficiency by 8.4%.

In [52], a household SWHS with solar panels coupled with a phase-change energy storage device was proposed. The system consists of a water tank, solar collectors, pipes, and a data acquisition system. The solar panel was 1800 mm long. The PCM memory was installed in the collection tube. The diameter, wall thickness, and length of the PCM memory cells were 42.16, 1.53, and 1.720 mm, respectively. In this study, $Ba(OH)2.8H_2O$ was used as PCM, while a small amount of $BaCO_3$ was used as a nucleating agent. U-shaped copper tubes were embedded in the PCM as heat transfer tubes. The results highlighted that the heat output of the system was lower than that of conventional water-in-glass vacuum-tube solar water heaters with the same collection area. However, if the system is run at a constant flow rate, excess energy can be stored and released to reheat the water when the sun's rays fade. As a result, the system exhibited better performance than conventional systems.

Reducing the proportion of diffuse global radiation or the initial water temperature improves solar water heaters performance. In [53], a new method was proposed to integrate dual PCMs into solar vacuum tube collectors for SWHS. The double PCMs used in the study were tridecane (melting point 72°C) and erythritol (melting point 118°C). The results showed that the PCM integrated into the inner tube of the vacuum tube solar collector can effectively store latent heat due to the thermal insulation of the vacuum tube. Therefore, when the sun is not strong enough, it delays supplying heat to the system. The outcomes revealed that the proposed SWHS with PCM integrated into the vacuum solar tube collector had an efficiency improvement of 26% and 66% in normal operation and stagnation mode, respectively, compared to the standard SWHS without PCM. When using an SWHS consisting of a vacuum Heat Pipe Solar Collector (HPSC) and an LHS tank filled with PCM, solar energy is absorbed by the heat pipe evaporator section and transferred to the Heat Pipe Condenser (HPC) section. Heat is stored in the LHS tank. The stored heat is then transferred to the water supply and heated through a series of finned tubes located within the LHS tank. The results showed that the thermal efficiency of the system was 38-42% and 34-36% on sunny and rainy days, respectively. Furthermore, when increasing the water flow from 50 to 80 l/h, the overall system effectiveness improved in the test area. The results also showed that the system had no thermal stratification effects. Table VI shows the performance of some recent solar collector designs.

TABLE VI. PERFORMANCE OF SOME RECENTLY DEVELOPED SOLAR COLLECTORS

Ref.	Performance of developed solar collectors
[49]	After the sun goes down in the afternoon, keep the collector temperature above 40°C for 4 hours.
[51]	Keep the water temperature above 50°C for 1 hour.
[52]	Continue to increase the temperature of the water tank for 2 hours after the sunlight decreases in the afternoon
[53]	Keep the water temperature above 40 °C for more than 2 hours, without PCM

It should be noted that some intrinsic parameters related to PCM materials, such as the thickness and coating uniformity, can affect solar collectors performance [54-46]. In [57], PCM with a coating layer thickness of 160.1 μm in the MA/NBR-0.5 pellet recorded the highest latent heat of melting and freezing compared to other coated samples, due to the formation of a thin and compact coating layer. Table VII summarizes some solar collectors integrated with PCMS with different system configurations.

TABLE VII. RECENT STUDIES ON SOLAR COLLECTORS INTEGRATED WITH PCMS

Ref	System Configurations	Findings
[54]	Use of stearic acid (K = 0.32-0.34 W/m) as a PCM	Maximum daily energy outputs of collector A were found to be 85.86% (simultaneous mode) and 84.27% (midday charging mode) at a high mass flow rate (0.5 LPM), and energy outputs were 19.41% and 21.35%, respectively, at a low flow rate
[55]	Combined utilization of phase-change materials and fins in addition to nanoscale fluids to enhance electrical efficiency.	When using PCMs, the thermal, electrical, and overall efficiency improved by 26.87%, 17.33%, and 40.59%, respectively
[56]	The PCM used in the study was Beeswax (INS No. 901) or yellow beeswax (CAS No. 8006-40-4)	The average efficiency of the CTC-GT test mode at a collector angle of 25°, 30°, and 35° was 30.7%, 31.9%, and 31.7%, while CTC-GT mode provided 27%, 29.9%, and 29.6%.
[58]	Heat Pipe ETC (HPETC) integrated with PCM embedded with porous copper	The system showed 85.64% energy efficiency compared to a system without PCM which showed 36.91% energy efficiency.

V. OPPORTUNITIES

The performance of a building-integrated SWHS is more dependent on the quality of the system design rather than the individual SWHS products. Solar collector effectiveness is only one part of the system's performance, and the thermal energy storage and transfer to end users are also critical to the final performance. Additionally, due to the unreliability of solar energy, many SWHS building integration projects opt for a further energy supply system, usually that of electricity or natural gas. More systems come into play when the solar thermal system fails at night or under adverse weather conditions. However, in practice, the two systems not only increase users initial installation cost but also pose a major challenge to the system design. Simultaneously a poor system design can lead to more energy waste and higher energy bills. For example, repeatedly boiling a large amount of water in a tank to maintain its operating temperature when a solar system is not in operation for a long time can consume a lot of electricity or gas.

VI. CHALLENGES

Solar water heaters use solar energy to heat water or heat pumps that use air heat. Water heating can be expensive and energy-intensive. Compared to electric hot water systems, solar water heaters can help households save significantly on electricity bills and reduce emissions by up to 3 tons per year. Solar water heaters adoption peaked in 2009 when the federal government introduced discounts to make the technology more attractive ahead of plans to phase out electric hot water systems [38]. Since then, the market share of SWHSs has continued to decline, with sales in 2016 decreasing by 15% from the previous year. This decline was seen in all states and territories except Tasmania, where sales increased slightly. The Northern Territory saw the greatest drop, with sales decreasing by almost 40%.

VII. CONCLUSION

This article provides a comprehensive investigation of recent innovations in solar water heaters, emphasizing their enhanced performance and cost-efficiency when incorporating advanced components such as PCMs. Despite the high installation and material expenses, solar water heaters save the cost of electricity if their use is long-term. Considering technology, vacuum tube solar collectors have the highest effectiveness, followed by black- and blue-coated solar collectors. Aluminum collectors come in the fourth place. Storage tanks competence was also examined, and it was obviously higher when the PCMs were encapsulated in spherical capsules or cylindrical containers. The addition of PCMs results in smaller water storage tanks that are capable of retaining hot water for a longer period. Encapsulated PCMs can be easily added to existing storage tanks. However, the performance of an integrated SWHS in a building is more dependent on the quality of the system design than the individual SWHS products. Emergent technologies such as artificial intelligence-based optimization to reduce health risks and improve long-term performance. These technologies aimed to achieve the technical feasibility of SWHS with PCM and may be future opportunities that can be used to develop mathematical models to simulate and optimize design options.

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